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Membrane processes for heating, ventilation, and air conditioning

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ABSTRACT

This article reviews literature on using membranes in heating, ventilation, and air conditioning (HVAC) applications. Membranes enable the separation of one species from another, and membranes allowing the selective permeation of water vapor can be used to condition air in buildings, potentially more efficiently than conventional HVAC equipment. After a brief background on membrane technology, this review focuses on the following processes: vacuum membrane dehumidification; membrane energy recovery ventilation; liquid desiccant dehumidification; liquid desiccant regeneration; evaporative cooling; and humidification. It highlights the design, modeling, and experimental research on these topics, and suggests areas for further research.

Contents

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1. Introduction

The temperature and humidity of the air in buildings needs to be controlled to maintain human comfort, prevent mold growth, and ensure building durability. This requires the addition and removal of sensible and latent energy, meaning that the air in buildings requires heating, cooling, dehumidifying, and humidifying to varying degrees depending on the location of the building and how the building is used. Research in the heating, ventilation, and air conditioning (HVAC) field has improved the methods for conditioning this air, but it is typically done in the same manner as it was decades ago: heating with direct combustion (usually natural gas in the United States), vapor compression heat pumps, or electric resistance heaters; and cooling and dehumidifying with vapor compression air conditioners.

There are some concerns about these current practices; concerns that must be addressed in any sustainable energy future. In the United States, conditioning air accounts for 48% of the primary energy used in buildings [1]. Cooling and dehumidification, mostly from vapor compression systems, accounts for a significant portion of the peak electric demand in hot climates. Regulations are also phasing out refrigerants (CFCs, HCFCs) because they damage the ozone layer or contribute to climate change. Controlling humidity with vapor compression systems is also becoming more difficult as energy improvements often reduce the building's sensible load (e.g., from improved insulation), but do not affect the latent load (e.g., from required ventilation or internal gains) [2].

Researchers are pursuing alternatives to these conventional practices, especially for cooling and dehumidification [3]. Advancements in artificial membranes enable new possibilities in this area. While traditionally used for industrial separations, such as reverse osmosis and gas separation [4–6], membranes provide a means to selectively transfer water vapor from one fluid to another.

The coupling between latent and sensible energy enables a variety of potentially energy-efficient HVAC processes. While the membrane itself does not save energy, it can enable or improve processes that do. Membranes provide a means to remove moisture from the air without cooling the air to the dew-point temperature. This could mean the elimination of environmentally harmful refrigerants from cooling systems. They also make energy recovery processes possible, where moisture is exchanged between two separate airstreams. Membranes can also improve absorptive and evaporative processes, which are used in technologies like absorption chillers, liquid desiccant dehumidifiers, and evaporative coolers; technologies that are energy-efficient, but have yet to reach their market potential.

Over the past 15–20 years, researchers have explored these uses of membranes in HVAC processes. Interest in this area remains high, as illustrated with recent research grants from the US Department of Energy through their Advanced Research Projects Agency focused on Energy (ARPA-E) [7], which funds researchers working on high-risk, innovative energy ideas. In 2010, 16 projects received funding through an HVAC-focused program (Building Energy Efficiency Through Innovative Thermodevices). Membranes were a key focus in six of these 16 projects.

The purpose of this review is to summarize the literature on membrane HVAC processes. It begins with background on membrane technology, which is not meant to be comprehensive, but instead to highlight topics and literature relevant to this article. Then, it describes the HVAC applications, mostly for cooling and dehumidification, and assesses research on designing, modeling, and testing these membrane processes and devices. The review concludes with future research needs and directions.

2. Membrane technology background

A membrane is a selective barrier between two phases and is typically used to separate one species from another. Membranes can be made of many materials, but polymers are most common. Fig. 1 shows a generalized schematic of a membrane process. The *feed* stream is supplied to one side of the membrane, the *permeate* permeates across the membrane, and the *retentate* is retained on the feed side of the membrane. In some cases, a *sweep* stream helps carry away the permeate.

The permeate is transferred across the membrane because of a chemical potential gradient, which can be from gradients in pressure, concentration, temperature, or electric potential. The first two are most important for the processes discussed in this review.

The key function of a membrane is selective separation. Membranes are characterized by their *permeability* and their *selectivity*. The permeability is the amount of a species crossing the membrane, per unit area and per unit driving force. The selectivity is the amount of the more permeable species crossing the membrane relative to others. A higher permeability means less membrane area for a given transfer rate, and a higher selectivity means a purer product stream, which can be either the permeate or the retentate.

For HVAC processes, water vapor is usually the permeate, and thus the membranes need to be permeable to water vapor and selective to water vapor over other species. We can achieve these characteristics with two membrane types: *dense* membranes and *porous* membranes. We can also distinguish membranes by their form: *flat sheet* or *hollow fiber*.

2.1. Membrane type: dense and porous

Membranes are typically separated into dense and porous categories based on their pore structure. Dense membranes have pores on the order of 0.1 nm and porous membranes have pores on the order of 0.1 μm. In dense membranes, water vapor adsorbs onto the polymer and diffuses through the polymer matrix on the molecular level. In porous membranes, the water vapor diffuses through the air/vapor mixture within the pore space. There is some transition region between these two where both mechanisms are important [8]. However, the two can be separated in this review because the pores used in the membrane processes of interest are not near this transition region.

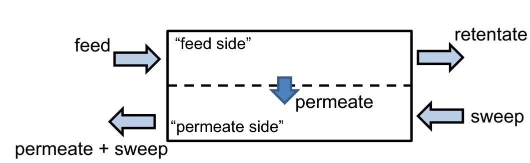

Fig. 1. Generic membrane process. Useful product stream can be retentate or permeate. Sweep is optional.

Nomenclature

A	area available for heat and/or mass transfer (m^2)
D	diffusion coefficient for water vapor through dense membrane ($m^2\ s^{-1}$)
D_{wa}	diffusion coefficient for water vapor in air ($m^2\ s^{-1}$)
D_K	Knudsen diffusion coefficient ($m^2\ s^{-1}$)
D_M	effective molecular diffusion coefficient ($m^2\ s^{-1}$)
d_p	mean pore size of membrane (m)
J_v	molar flux (kmol $m^{-2}\ s^{-1}$)
M_w	molar mass of water (18 kg $kmol^{-1}$)
p_v	vapor pressure (Pa)
P	permeability (kmol $Pa^{-1}\ m^{-1}\ s^{-1}$)
q	heat flux (W m^{-2})
R	universal gas constant (8314 J $kmol^{-1}\ K^{-1}$)
R_{HT}	heat transfer resistance (m^2 K W^{-1})
R_{MT}	mass transfer resistance (Pa m^2 s $kmol^{-1}$)
S	water vapor solubility in membrane (kmol $m^{-3}\ Pa^{-1}$)
T	temperature (°C)
t	membrane thickness (m)
y_{air}	mole fraction of air
ε	membrane porosity
τ	membrane tortuosity

2.1.1. Dense membranes

Dense membranes (e.g., see [6]) are polymer films where the intrinsic properties of the membrane material, specifically a kinetic property (diffusivity) and a thermodynamic property (solubility), determine the permeation rate. A molecule will adsorb onto the polymer surface, diffuse through the bulk polymer due to a concentration gradient, and then desorb from the other surface (Fig. 2). These membranes are used in gas separation processes, such as separating O_2 from N_2, CO_2 from combustion gases, or water vapor from air. Polyimide membranes are an example. They have a high permeability to CO_2 because of the physical and chemical interactions between CO_2 and polyimide. Polyimide interacts differently with methane (CH_4), resulting in a lower permeability. This enables polyimide membranes to separate CO_2 from CH_4, with a CO_2/CH_4 selectivity on the order of 10–100.

Membranes for transferring water vapor are *hydrophilic*, meaning they have a strong affinity to water. Water is very soluble in these membranes, resulting in high permeability and a water/air (or H_2O/N_2) selectivity of up to 100,000 [9–11]. This means that 100,000 molecules of water pass through the membrane for every single molecule of nitrogen, assuming equal driving potentials. Higher permeability means less area is needed for a given process, and high selectivity allows for removal of water vapor from an airstream without removing much air. Increasing the water vapor permeability and the water/air selectivity of these membranes is the focus of many researchers, who have looked at new polymer materials [9,12,13], ceramic materials [14], liquid membranes [15–19], and composite membranes [6,20–22]. A 2009 ARPA-E grant funded ADMA Products, Inc. to develop a coated metal membrane specifically for air conditioning applications [23].

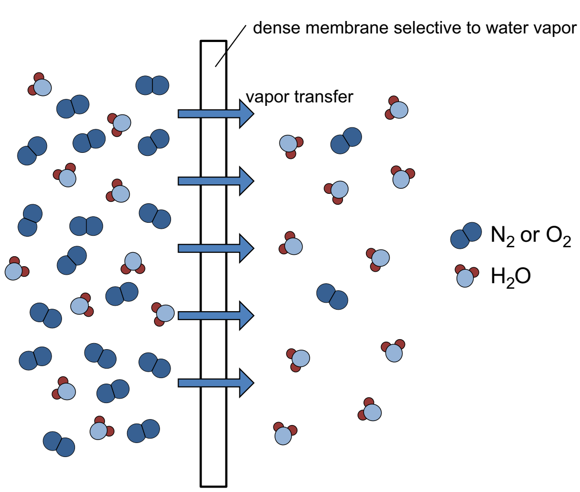

Fig. 2. Membrane–fluid interface for dense membrane.

Composite membranes deserve some further explanation, as these are fairly common and significantly improve permeability. Permeability is inversely proportional to the membrane thickness, so making very thin membranes is one way of creating highly permeable membranes. Composite membranes are created by combining a thin dense layer, on the order of 1 μm thick, to a highly porous support structure, on the order of 100 μm thick. The support layer provides mechanical strength, but adds little resistance to vapor transfer compared to the dense layer.

2.1.2. Porous membranes

Porous membranes have more open volume and larger pores than dense membranes. Researchers developing prototypes for HVAC devices used porous membranes with pore sizes ranging from 0.03 to 1 μm, and porosities ranging from 40% to 70% [24–28]. The porosity, which is between 0 and 1, is the volume of the pores (i.e., open space) divided by the bulk membrane volume.

Porous membranes are used to contact a liquid with a gas, as opposed to the gas/gas contact where dense membranes are used. These liquid/air modules are a subset of *membrane contactors*, which have been reviewed by Drioli et al. [29]. Similar membranes are also used in membrane distillation and osmotic distillation [30–32], where volatile liquids evaporate from one liquid stream and condense into another liquid, selectively separating them from less volatile liquids and solids.

The separation mechanism for porous membranes differs from dense membranes. The pores are larger so that water vapor diffuses through the pore space, instead of through the solid polymer matrix. Unlike dense membranes, the membrane material is *hydrophobic* (e.g., polypropylene); the water molecules are more attracted to each other than they are to the solid material. This produces surface tension forces that keep the liquid from entering the pores and creates a liquid/gas interface at the membrane surface (Fig. 3). The required *entry* or *breakthrough* pressure, which is the pressure where liquids enter the pores, is proportional to the water/material surface tension and inversely proportional to the pore size. It is typically on the order of 10–100 psi, but it is lowered substantially if surfactants contaminate the liquid [30].

Permeability can be increased by making the membranes thinner, with larger pores, and with a higher porosity (see Eqs. (8)–(10) in Section 4.1.1); however, there are trade-offs. Larger pores increase the likelihood of pore breakthrough and liquid entry, and thin membranes can be less durable. Membranes as thin as 20 μm have been used [33], but there are questions about their longevity. One possibility is to use *asymmetric* membranes, where a relatively thick, highly porous layer is used to provide structural support, and a thin layer with small pores (1–10 nm) ensures no liquid entry. These can be made in different ways. A thin porous membrane can be attached to a highly porous

substrate [26], a dense coating can be applied to a porous membrane [34,35], or a membrane with an asymmetric structure can be made in one step [36,37].

2.2. *Membrane form: flat sheets and hollow fibers*

In addition to the microscopic structure of the membrane, we can also distinguish between two macroscopic structures, or forms: flat-sheet membranes and hollow-fiber membranes. Flat-sheet membranes are large sheets, usually on the order of 100 µm thick. They are used to construct modules similar to plate-and-frame heat exchangers (Fig. 4a).

Hollow fibers are tubes, typically around 500 µm in diameter, where the wall of the tube is the membrane. They are used to construct modules similar to shell-and-tube heat exchangers (Fig. 4b). In these modules, one fluid flows inside the tubes (the *lumen* side) and the other flows around the tubes (the *shell* side).

Both forms can be used in membrane HVAC devices. The reasons for using one over the other are specific to the application, so they are discussed in the next section.

3. HVAC applications of membranes

This review focuses on five common membrane HVAC processes. Table 1 lists the inlet and outlet streams, as they are labeled in Fig. 1, and also shows which processes require dense, hydrophilic membranes, and which require porous, hydrophobic membranes. Sections 3.1–3.4 describe these processes in more detail (liquid desiccant regeneration and dehumidification are discussed in the same section). Some less common processes are described briefly in Section 3.5.

3.1. *Vacuum membrane dehumidification*

Vacuum membrane dehumidification uses a pressure gradient to transfer vapor across a dense, hydrophilic membrane (Fig. 5). Water vapor adsorbs into the membrane, diffuses through the membrane, and desorbs from the membrane on the low-pressure side. This low pressure is created with a compressor, or vacuum pump. The H_2O/N_2 selectivity of the membrane is important, so that the compressor pulls primarily water vapor through the membrane.

A similar process, referred to as membrane drying, is used for removing moisture from a variety of gas streams. Wang et al. [20] discussed drying of compressed air, where the compressed air is delivered to the lumen-side of hollow fibers, and ambient-pressure

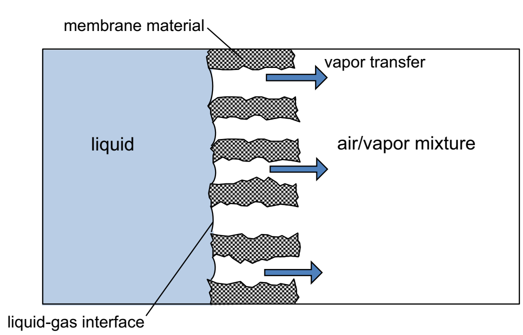

Fig. 3. Membrane–fluid interface for porous membrane. Pores are generally tortuous and interconnected, but they are shown as straight-through pores here for simplicity.

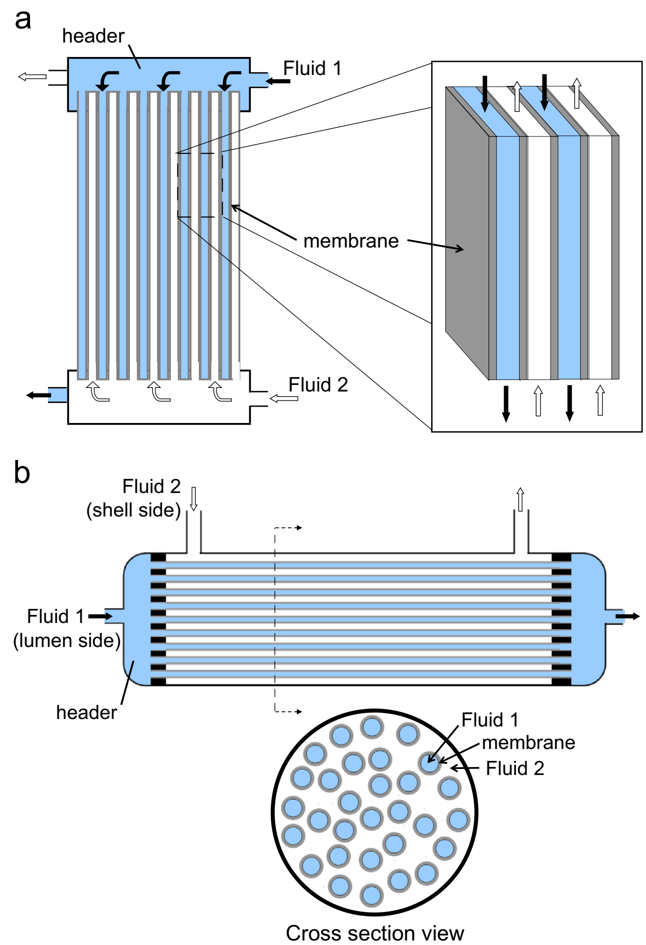

Fig. 4. Schematic of (a) flat-sheet module and (b) hollow-fiber module.

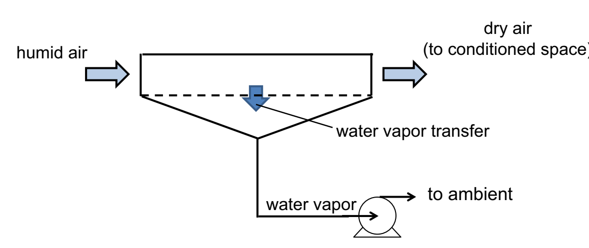

Fig. 5. Schematic of membrane vacuum drying.

Table 1
Summary of membrane HVAC applications. Note that evaporative cooling and humidification are combined since their characteristics are the same.

	Feed	Retentate	Sweep inlet	Sweep/permeate outlet	Membrane type
Vacuum membrane dehumidification	Humid air	Dry air[a]	N/A	Water vapor	Dense, hydrophilic
Membrane energy recovery ventilator	Hot, humid air	Dry, cool air[a]	Dry, cool air	Hot, humid air[a]	Dense, hydrophilic
Liquid desiccant air conditioning	Warm, humid air	Hot, dry air[a]	Concentrated LD	Diluted LD	Porous, hydrophobic
Liquid desiccant regeneration	Diluted LD	Concentrated LD[a]	Ambient air	Humid air	Porous, hydrophobic
Evaporative cooling/humidification	Water	Water	Hot, dry air	Cool, humid air[a]	Porous, hydrophobic

[a] Useful product stream or streams.

gas is delivered to the shell side, creating a pressure gradient across the membrane. Compressing the air flow rates used in space conditioning would be impractical and energy inefficient, but using a compressor on the permeate side is an alternative way to apply a pressure gradient [38]. This means the compressor only needs to compress the water vapor (and the very small amount of air) that crosses the membrane. In 2000, El-Dessouky et al. [39] proposed this process for HVAC applications. They modeled their system with a membrane having a H_2O/N_2 selectivity of 400, but as discussed in Section 2.1.1, a selectivity over 100,000 is possible.

3.1.1. Module design

A vacuum membrane dehumidifier is made by assembling highly permeable, highly selective membranes into a module. These can be flat-sheet or hollow-fiber membranes. El-Dessouky et al. [39] modeled a hollow-fiber module, but they did not build a prototype, and although Scovazzo et al. [40] suggest using a hollow-fiber module for this process, they built a small (10 cm^2) flat-sheet prototype for their experiments. Hollow fibers are more likely in commercial applications because their structure enables them to withstand the large pressure differences between the airstream (~100 kPa) and compressor inlet (~1 kPa).

Supplying the air to the lumen side of the hollow fibers, as done by Wang et al. [20], can lead to large pressure losses [40]. Supplying the air to the shell side instead has less pressure loss, but it can potentially result in poor flow distribution [41–43]. Some researchers have suggested modules where the air flows around a structured arrangement of fibers on the shell side [35,40], making distribution more uniform.

In addition to ensuring good distribution, the module should also minimize the mass transfer resistance in the gas boundary layers next to the membrane. The concentration of water vapor at the membrane surface is not the same as the concentration in the bulk flow. This *concentration polarization* affects performance, as discussed by several researchers [9,10,20]. It means that the actual permeability is less than that of the membrane alone. Since concentration polarization increases as the permeation rate increases, this effect is more important for highly permeable membranes [10].

The increase in concentration polarization as the permeation rate increases also reduces the selectivity. The low transfer rate of air leads to nearly negligible concentration polarization for air, while the high transfer rate of water vapor results in high concentration polarization. In other words, the largest resistance to air transfer is the membrane, while the largest resistance to water vapor transfer is the gas film next to the membrane. Data from Wang et al. [20] illustrate this. They calculate the selectivity of the membrane to be 30,000, but the actual measured selectivity (including boundary layers) ranged from 30 for low airstream flow rates to 300 for higher flow rates. These drastic differences show the importance of including the boundary layer resistances in modeling this process.

3.1.2. System design and analysis

Researchers have designed, built, and tested many membrane modules for gas separation and membrane drying, but most of it has focused on industrial separation processes as opposed to comfort cooling for buildings. Thus, there is little research on system design for comfort cooling. The two metrics to consider are the energy efficiency of the process (i.e., operating costs) and the size of the compressor and membrane module (i.e., initial costs).

This process has the potential to be much more efficient than a vapor-compression dehumidifier, which condenses water vapor out of the air by cooling the air below the dew point. The key is to minimize the energy required to create the pressure gradient across the membrane.

While this process looks promising on paper, there are some practical limitations. To illustrate this, consider the example shown in Fig. 6, which roughly corresponds to a 10-kW residential air conditioner. The inlet and outlet humidity is indicated with the vapor pressure, p_v, which correspond to typical inlet and supply dew point temperatures of 16 °C and 10 °C, respectively. The required water vapor flow rate (0.14 kg/min) is calculated based on this change in humidity and the assumed airstream flow rate.

To calculate the efficiency of this process, we use the same dehumidification efficiency equation used by Scovazzo et al. [40] (see also [44]). Since the desired vapor pressure of water in the exiting airstream is 1.25 kPa, the compressor must reduce the pressure to below 1.25 kPa. If the water vapor is discharged from the compressor to ambient air, as it is in El-Dessouky [39], the compression ratio is at least 80 (101 kPa/1.25 kPa). To minimize the membrane module size, the membrane requires a finite driving force across it. Thus, the pressure will more likely be near 1 kPa and the compression ratio 100. Using a compression ratio of 100 and assuming a compressor efficiency of 60%, the calculated dehumidification efficiency is 200%. This means that for every one unit of electrical energy input, there are two units of latent energy removed from the airstream.

Regardless of the efficiency, this process requires large, complex compressors that are not suitable for building air conditioners. The flow rate of 0.14 kg/min is around 5.4 m^3/min, or 200 cfm, at that pressure. Pulling this much volume through the compressor at a compression ratio of 100 will require a large compressor with at least two stages of compression [44]. It will also need significant cooling (adiabatic compression will lead to temperatures of several hundred degrees Celsius). This will be impractical for most air conditioning applications. But some researchers are modifying the process to try to address these issues.

Scovazzo et al. [40] attempt to solve these issues by using some of the air that has already been dehumidified as a sweep gas (Fig. 7), which is a common method for membrane drying of compressed air [20,38]. The air exiting the feed side is at ambient pressure with a water vapor pressure of 1.25 kPa. When the

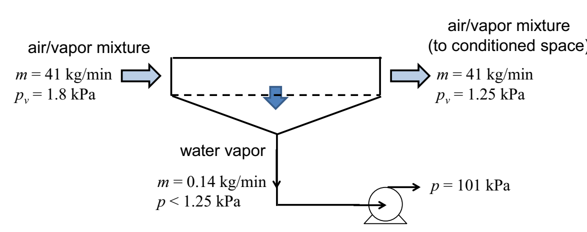

Fig. 6. Illustrative case considered for vacuum membrane dehumidifier: m=mass flow rate, p=pressure, p_v=vapor pressure. Flow rates, pressures, and vapor pressure values are illustrative.

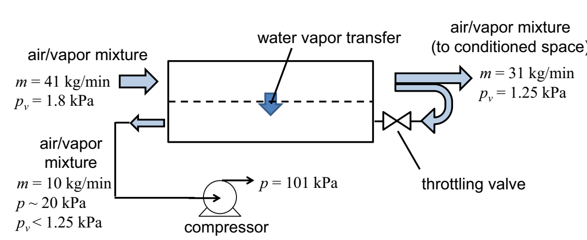

Fig. 7. Schematic example of alternative vacuum membrane dehumidifier investigated by Scovazzo et al. [40]. Flow rates, pressures, and vapor pressure values are illustrative.

pressure is reduced through the throttling valve, the vapor pressure is also reduced (vapor pressure = pressure × concentration). Thus, achieving a vapor pressure below 1.25 kPa is possible at much higher absolute pressures, reducing the compression ratio from 80 to around 5–10. This eases the requirements for the compressor, and can also improve the compressor efficiency. It does not necessarily improve the process efficiency because some of the dehumidified air is being discarded with the sweep and thus is not provided to the space.

Another alternative design, investigated by Dais Analytic Corporation [45], is to pump the vapor to a lower vapor-pressure sink instead of the ambient pressure of 101 kPa. In this concept, the compressor discharges the water vapor into a second membrane module, which puts the low-pressure vapor in contact, through a membrane, with ambient air (Fig. 8). Thus, the compressor only needs to pump up to the ambient vapor pressure, instead of the ambient absolute pressure.

The compression ratio in this concept, and therefore the dehumidification efficiency, depend on the ambient humidity (i.e., dew-point temperature). The compression ratio is simply the ratio of the pressures between the two membrane exchangers (3.5/1.25 in the illustrative example in Fig. 8), and, as before, the dehumidification efficiency can be calculated based on the equation from Scovazzo [40]. The result is shown in Fig. 9 assuming a 0.25 kPa driving potential in each membrane exchanger, inlet and outlet conditions shown in Fig. 8, and a compressor with an efficiency of 60%. Note that this does not include the electrical energy for the fans required to push the air through either of the membrane exchangers. Dais received funding from ARPA-E in 2009 to advance their concept further [23], but there is little information about this technology available in the open literature.

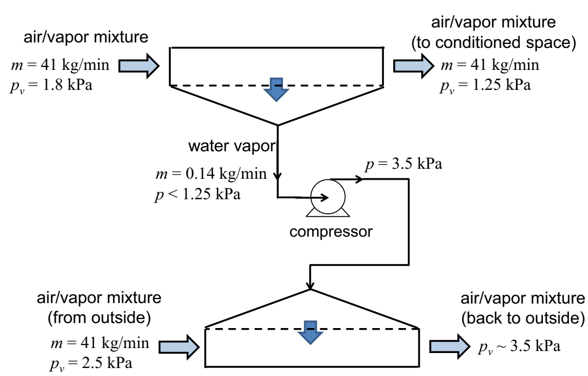

Fig. 8. Schematic example of alternative vacuum membrane dehumidifier investigated by Dais Analytic [45]. Flow rates, pressures, and vapor pressure values are illustrative.

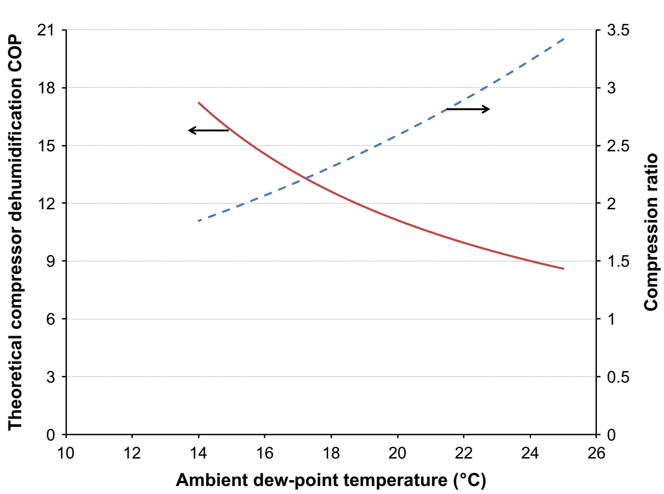

Fig. 9. Theoretical compression ratio and dehumidification efficiency (COP = coefficient of performance) versus ambient dew-point temperature for the design shown in Fig. 8.

The Dais concept also includes a membrane evaporative cooler, a concept which is explained in Section 3.4. The low relative humidity (RH) exiting the vacuum dehumidifier enables this evaporative cooling. This is not possible with vapor compression systems, which supply air near saturation. Combining these two devices offers a way to decouple the latent and sensible loads, with the vacuum dehumidifier providing latent cooling and the evaporative cooler providing sensible cooling. El-Dossouky et al. [39] modeled a (non-membrane) indirect evaporative cooler at the exit of the membrane dehumidifier and illustrated the energy savings potential of this concept.

3.2. Membrane energy recovery ventilators

Membrane-based energy recovery ventilators (ERVs) use dense membranes similar to those used in vacuum membrane dehumidification, but the operating principle is different (Fig. 10). The compressor is replaced by a low-vapor-pressure sweep stream, and the absolute pressure gradient across the membrane is replaced by a vapor pressure difference. Like heat exchangers, these devices transfer sensible energy between the two airstreams, but they also transfer latent energy via water-vapor diffusion. They are used to exchange sensible and latent energy between a building's exhaust air and its incoming ventilation air. Thus, it supplies lower energy ventilation air in the summer and higher energy ventilation air in the winter, reducing the required space conditioning.

Researchers converted sensible heat exchangers into these ERV devices more than 30 years ago, by replacing the thermally-conductive heat exchange surfaces with vapor-permeable paper sheets [11,46]. More recently, Zhang and Jiang [47] replaced these paper sheets with dense, hydrophilic polymer membranes. They modeled and measured the effectiveness of a cross-flow membrane ERV and compared it to the effectiveness of a sensible-only metal heat recovery ventilator (HRV) and a paper ERV. This effectiveness can be split into sensible, latent, and total, which are often used to characterize ERVs. Assuming equal flow rates, these are calculated with [48]

$$\varepsilon_{SENS} = \frac{T_{1,out} - T_{1,in}}{T_{2,in} - T_{1,in}} \tag{1}$$

$$\varepsilon_{LAT} = \frac{\omega_{1,out} - \omega_{1,in}}{\omega_{2,in} - \omega_{1,in}} \tag{2}$$

$$\varepsilon_{TOT} = \frac{h_{1,out} - h_{1,in}}{h_{2,in} - h_{1,in}} \tag{3}$$

where T, ω, and h are respectively the air temperature, humidity ratio, and enthalpy, the subscripts 1 and 2 indicate the two different airstreams.

Zhang and Jiang [47] showed that a membrane provides roughly two times more latent recovery than paper under hot, humid conditions. Since the HRV recovers only sensible energy, the latent effectiveness of the HRV is zero. Because much of the energy during this hot, humid condition is latent, the total energy

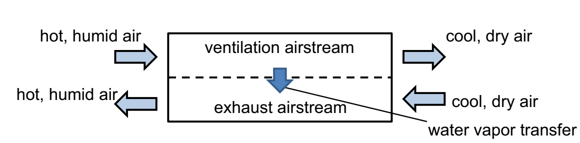

Fig. 10. Operating principle of membrane ERV in summer. In the winter, exhaust and ventilation airstreams are switched.

transfer of the membrane ERV was 4.8 times higher than the HRV and 1.7 times higher than the paper ERV. For cold conditions, the sensible energy recovery generally dominates over the latent recovery; thus, the benefits for cold climates is smaller. Zhang et al. estimates that the membrane ERV has 1.3 times higher energy transfer than the HRV in Beijing (a cold climate) [49]. Similar conclusions can be drawn from other studies looking at different climates [50–54].

Over the last decade, several manufacturers have developed membrane ERV products. These compete against other energy recovery technologies, as discussed in a recent review by Mardiana-Idayu and Riffat [55]. Fig. 11 plots data from a standard test performed by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) on several commercially available membrane ERVs from about a dozen manufacturers. The data shows that the latent effectiveness is generally less than the sensible effectiveness. Some of the reasons for this are discussed in the next section.

3.2.1. Module design

The dense, hydrophilic membranes used for membrane ERVs typically have high water permeability and high water/air selectivity, like the membranes for vacuum dehumidifiers. But the absolute pressure difference across the membrane is orders of magnitude smaller, making the construction requirements less stringent. This low pressure difference also means that it is not the water/air selectivity that is important, but rather the selectivity of water vapor over various pollutants (e.g., CO, CO_2, volatile organic compounds (VOCs)) [56]. Unlike air, the concentration differences of pollutants across the membrane can be large, and the membrane must be selective to water vapor over these pollutants.

Measurements have shown that selectivity of water over pollutants is generally smaller than the H_2O/N_2 selectivity. Wang et al. [20] measured the permeability of a particular dense membrane to H_2O, CO_2, and N_2, and calculated an H_2O/CO_2 selectivity that was 15 times smaller than the H_2O/N_2 selectivity. Zhang et al. [56] measured the permeability of water vapor and several VOCs through membranes made of different materials. They found selectivity values in the range of 100–400. While these are still adequate for removing most pollutants from buildings, it may be a poor assumption to assume no pollutants cross the membrane along with the moisture.

Like vacuum dehumidification, concentration polarization is present in ERVs, and the module should be designed to minimize these airside resistances. A comparison between a membrane ERV and a sensible-only HRV illustrates the importance of these airside resistances. Since the air thermal diffusivity and the mass diffusivity of water vapor in air are roughly equal, the airside resistances for mass transfer and heat transfer should be roughly equal. Zhang and Jiang [47] showed that a membrane ERV provides roughly the same sensible energy transfer as a metal HRV, even though the membrane thermal conductivity is orders of magnitude lower than that of the metal plates. This indicates that most of the heat transfer resistance must be coming from the air boundary layers. Indeed, Kistler and Cussler [51] estimated that the air boundary layer accounts for more than 95% of the overall heat transfer resistance.

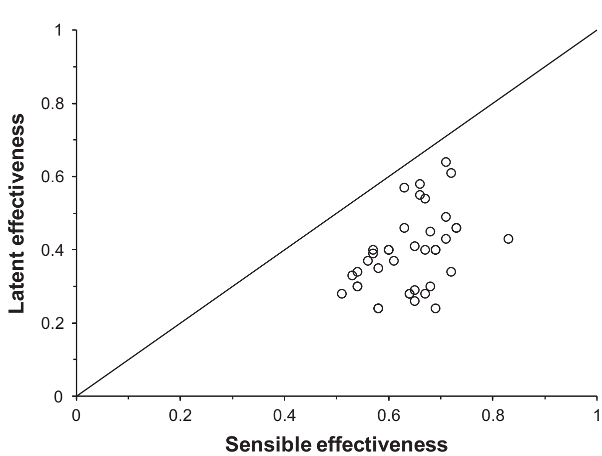

Fig. 11. Latent and sensible effectiveness of membrane ERV units tested according to AHRI standards [140].

The importance of the airside boundary layers for mass transfer is estimated to be much smaller; Zhang [57] calculated that they account for 25% of the total resistance, while Min and Su [58] estimated that they account for 10–35% of the total. This means the membrane mass transfer resistance is not negligible, and this is why the latent effectiveness in Fig. 11 is always lower than the sensible effectiveness. It is also why some points in Fig. 11 give three times more latent transfer than others; the points with higher latent transfer use more permeable membranes. This also means that, for some membranes, the airside resistances are not as important. Using the membrane permeability from [59], the airside resistance becomes roughly 75% of the total. These modules with high performing membranes are near the 45° line in Fig. 11. They provide nearly as much latent recovery as sensible, which shows that in some modules the airside resistances for mass transfer are becoming important.

These airside boundary layers are a function of the module construction. The modules can be made with either hollow-fiber or flat-sheet membranes. Flat sheets are more common, and to the author's knowledge, all commercially available units use flat-sheet membranes. One disadvantage of flat sheets is that they are not self supporting, so that a spacer must be used to reinforce the membrane. As several researchers have noted [60–62], an unsupported membrane can deflect or bulge into the airstreams, which affects performance by reducing the effectiveness of the exchanger [60,63]. Larson et al. [60] modeled and measured mass flow rates in the air channels for different amounts of membrane deflection. They recommended pre-tightening the membranes, which will reduce their deflections. Even with pre-tightening, the membranes may still require a support spacer to maintain uniform channel thicknesses.

Regardless of whether or not spacers are needed, they can be useful for enhancing heat and mass transfer in the airside boundary layer. However, they will also increase the pressure drop in the channel. A few studies have focused on understanding this tradeoff between heat/mass transport and pressure drop [57,62,64–66]. More extensive research has analyzed a similar tradeoff in liquid-to-liquid membrane processes [67–71].

While flat-sheet modules are more common, hollow-fiber modules can also be used as membrane ERVs. Kistler and Cussler [51] looked at both types, but they were interested in hollow fibers because of their ease of construction. One disadvantage of hollow fibers is their large pressure drop. Zhang [72] measured a pressure drop for their 1.2-mm i.d. fiber lumens of around 350 Pa. The pressure drop in the module used by Kistler and Cussler [51], which had 0.6-mm i.d. fibers, were likely much higher, but they were not reported. Pressure drops above 350 Pa are unlikely to be used in these devices because fan initial cost generally increases with the supplied pressure, and because of increased parasitic energy use. For contrast, Mardiana-Idayu and Riffat [73] reported pressure drops for their flat-sheet modules of 30 Pa, and pressure drops for most commercially available units range from 100 Pa to 300 Pa.

One final consideration in module design is the orientation of the airstreams. Most are crossflow, due to easier construction, but some researchers have also looked at designing flat-sheet modules

to be at least partially counterflow [53,74], which offers better performance.

3.2.2. System design and analysis

The energy savings of an ERV are directly proportional to the sensible and latent effectiveness. They are also impacted by the parasitic energy use by the fans that are needed to move the air. So from an energy perspective, the optimal design will have high effectiveness and low pressure drop.

The effectiveness of membrane ERVs depends on the flow rate per membrane area. Prototypes and commercially available modules are typically sized to give sensible and latent effectiveness values of around 60–80% [59,61,62,75,76], although as mentioned before, the latent effectiveness is typically lower than the sensible effectiveness. The values in Fig. 11 are for a single condition, which is reasonable for the sensible effectiveness; any variation in the conductivity of the membrane will have a small impact on performance because the airside resistances dominate. The latent effectiveness, though, varies with the inlet air conditions; the membrane's permeability varies more with temperature and humidity, and the membrane resistance is not negligible.

The dependency of permeability on the air temperature and humidity can be understood with the data from Zhang et al. [49]. Plotting their 15 measured latent effectiveness values versus the inlet RH indicates a strong positive correlation (plot not shown here for brevity). The slope of the best-fit line indicates approximately a 7 percentage point increase in latent effectiveness for every 10 percentage point increase in RH, over a range of 28–50% RH. By contrast, there is no correlation between the sensible effectiveness with either temperature or RH.

The variation in membrane permeability with RH could be due to either the slope of the sorption curve (i.e., solubility) or the diffusivity, but most researchers have focused on the former. Zhang et al. [59] calculated the slope of the sorption curve as a function of RH, showing a steeper curve at higher RH. Min et al. [77] showed similar trends with their measurements on three membranes. Niu and Zhang [78] modeled hypothetical materials with different sorption curves and quantified this effect. They showed that a linear sorption curve (i.e., constant slope) is generally preferred, but noted that for polymers the curve is typically concave, meaning steeper curves, and therefore higher permeability, at higher RH (see Eq. (7) in Section 4.1.1). Since pressure drop is not a strong function of inlet condition, this variation in permeability changes the energy performance depending on the location and season.

Other factors impact the performance of an ERV. Kosar [79] quantified the effect of unbalanced airflows, where the exhaust airflow is less than the incoming ventilation air because of air being exhausted at other locations (e.g., a kitchen exhaust fan). This reduces the capacity of the ERV. Zhang [63] looked at the maldistribution of the airflows (e.g., from one channel to another) due to improper installation within the ducting system. This also degrades performance. Several researchers [50,80,81] looked at how control methods can affect performance. For example, in the summer there may be times when the indoor temperature and humidity are higher than outdoors because of internal gains (e.g., equipment, people). Operating an ERV during these times *increases* energy use because the exhaust air adds sensible and latent energy to the incoming ventilation air. Although more research is needed, some possible control strategies have been proposed to minimize this undesirable operation [81].

3.3. Liquid desiccant dehumidification

Liquid desiccant dehumidifiers perform the same function as membrane vacuum dehumidifiers, but the process is driven by vapor pressure gradients set up by a low-activity aqueous solution (i.e., liquid desiccant), rather than the pressure gradients from a compressor. Fig. 12 is a schematic of a liquid desiccant membrane dehumidifier, which consists of two membrane exchangers: a conditioner and a regenerator. In the conditioner, moisture passes from the air through a porous, hydrophobic membrane and into the desiccant. The desiccant is then heated, so that in the regenerator, water evaporates out of the desiccant and into a separate airstream. This concentrates the desiccant so it can re-absorb moisture in the conditioner.

Using a membrane offers several benefits, primarily because the liquid desiccant is contained and separated from the airstreams. Many of these dehumidifiers spray a high flow rate of liquid desiccant into the airstream [82], which often leads to liquid desiccant entrainment in the air. Because the liquid desiccant is corrosive, this *carryover* can damage ductwork, other HVAC equipment, and building components. Using a low flow rate of liquid desiccant on a wicked surface reduces this carryover [83], but using a membrane eliminates it. For the regenerator, containment is not as critical; the air is not entering the building. However, containment still reduces the risk of corrosion, and using membranes in both the regenerator and conditioner prevents some air pollutants from contaminating the desiccant [24]. In addition to containing the desiccant, membranes also provide a constant area, which can be maintained even at part load [24,84].

3.3.1. Module design

The membrane modules for both the conditioner and regenerator bring liquid desiccant and air into contact on opposite sides of a porous membrane. The modules for both are similar; it is primarily the operation that differs: high liquid desiccant temperatures lead to desorption (regenerator), low temperatures lead to absorption (conditioner). One difference in design, though, is that the membrane in the regenerator must be able to withstand elevated temperatures (up to 90 °C) and the temperature swings between these elevated temperatures and ambient. As noted by Conde [84], a membrane regenerator is susceptible to leaks because of thermal expansion mismatches.

In both the conditioner and regenerator, hollow fibers offer some advantages over flat sheets. The structure of the hollow fibers inherently supports the liquid pressure, eliminating any membrane deflection. Hollow fibers also provide a higher surface area to volume ratio, which is illustrated by comparing the 0.015 m^2 membrane area in the flat-sheet module used by Isetti et al. [24] with the 1.13 m^2 membrane area in the hollow-fiber module used by Bergero and Chiari [25]. Hollow fibers are also easier to seal, with all of the sealing taking place at the two *headers* (Fig. 4b), instead of around the edges of each flat-sheet membrane. A simple method for making small-scale, hollow-fiber modules was documented by researchers at the Georgia Institute

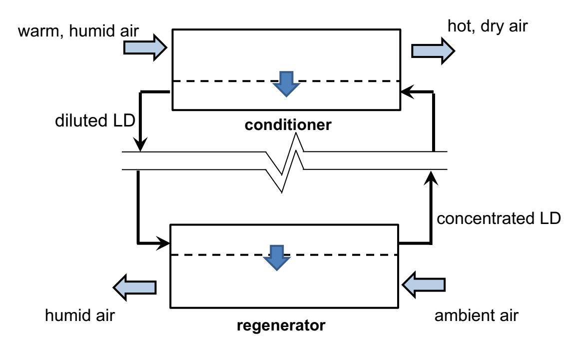

Fig. 12. Schematic of liquid desiccant dehumidification. Break lines are used for simplicity; the process generally has components (e.g., tank, pumps, heat exchangers) between the regenerator and conditioner that depend on the configuration.

of Technology, which can be found in the appendices of some theses (e.g., [85]).

These hollow-fiber modules typically look like the module in Fig. 4b, but there are two issues with this design, both related to the air flow on the shell side: high pressure drop [35], and poor airflow distribution [41,42]. The airside pressure drops are generally higher than in flat-sheet modules, but this also means the airside resistances are typically small, with the largest resistance typically coming from the membrane [36]. Kneifel et al. [35] proposed a transversal flow hollow-fiber module to improve flow distribution, where frames of hollow fibers are stacked together, with each set perpendicular to the airstream.

Using flat sheets instead can reduce this pressure drop, but they have a lower area to volume ratio and generally have lower overall mass transfer coefficients due to slow airside transfer [86]. Similar to membrane ERVs, spacers or enhancements can be used to reduce the airside resistance, as in [26]. These spacers also help support the membrane [87]. Several researchers have looked at flat sheet membrane contactors for desiccant-air modules [88–90].

The primary advantage of flat-sheet membranes, though, is that they enable a third fluid stream that can integrally cool the conditioner or integrally heat the regenerator, as shown in Fig. 13. If the membrane module contains only two fluids, the liquid desiccant must be heated prior to entering the regenerator and cooled prior to entering the conditioner. Alternatively, a three-fluid module, which is easier to construct with flat-sheet membranes, enables cooling of the desiccant internal to the conditioner and heating of the desiccant internal to the regenerator.

This integral heating and cooling offers advantages over an adiabatic dehumidifier. Internal cooling in the conditioner keeps the vapor pressure of the desiccant low, which leads to larger driving forces [26]. Compared to a non-cooled conditioner, this translates into either a lower required surface area or dryer air, or both. Liquid desiccant flow rates are lower because the cooling fluid provides the heat capacity to carry away the heat of absorption; without integrated cooling, the liquid desiccant must provide this heat capacity [91]. This also means lower pump energy. In the regenerator, the larger driving forces from internal heating enable a smaller device and also make it easier to concentrate the desiccant to a higher concentration. The heating fluid maintains the desiccant temperature, even for low desiccant flow rates.

Two research groups recently built conditioners using membranes with internal cooling. Conde and Weber [84,92,93] constructed a prototype conditioner with internal cooling, and also a regenerator with internal heating [84]. The conditioner was a flat-sheet device with 14 air channels and a total area of 4.6 m^2. Conde and Weber [93] also attempted to construct a shell-and-tube module, where the flat sheets were wrapped around a metal tube containing the chilled water. This assembly process was difficult and damaged the membranes. The flat-sheet prototypes were also difficult to assemble, particularly the detailed machining and the adhesion of the membrane to the plate. Once assembled, the adhesive swelled, causing misalignment of some liquid manifolds and leaking, especially for the regenerator, which saw much larger temperature swings [84]. They suggest that the assembly and reliability of the module could be improved with injection-molded parts and thermal welding of membranes instead of adhesion [84].

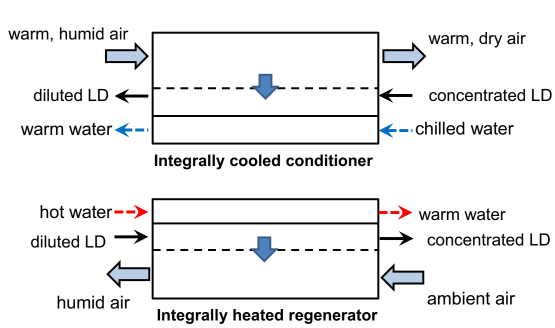

Fig. 13. Flat-sheet designs of integrally cooled conditioner and integrally heated regenerator.

Kozubal et al. [33,94] pursued a similar device, but with an evaporatively cooled airstream replacing the chilled water, which eliminates the need for a cooling tower or chiller. They tested two prototypes, one with 41 channel pairs and a surface area of 10.2 m^2 [33], and one with 36 channel pairs and a surface area of 12.1 m^2 [26]. Again, the sealing of the membrane edges was challenging.

3.3.2. System design and analysis

While using membranes in liquid desiccant air conditioners is relatively new, liquid desiccant systems by themselves are not new. The advantages and energy-savings potential of liquid desiccant systems have been reviewed previously [91,95], whether they use membranes or not. Their primary advantage is that they replace some electrical energy input with thermal energy, reducing the peak electric demand and benefiting utilities. They also reduce energy use in buildings requiring strict humidity control, or in supermarkets that have large refrigeration systems. For more details, see [91,95–97].

Some researchers have specifically looked at system efficiencies and benefits when using membrane modules. The membrane contains the liquid desiccant, which is beneficial if the system design requires several fluids interacting in one heat and mass exchanger. One of these concepts, integrated cooling of the conditioner, was discussed above. Another option is to combine liquid desiccant dehumidification with another cooling device, either evaporative cooling or vapor compression cooling.

Combining liquid desiccant systems with evaporative cooling can lead to significant energy savings because liquid desiccants provide low RH air (similar to the vacuum dehumidifiers discussed in Section 3.1). This results in independent control of latent and sensible cooling. Conde and Weber [92] combined a membrane evaporative cooler with the liquid desiccant dehumidifier, both made with flat-sheet membranes (see Section 3.4 for more on membrane evaporative cooling). The concept investigated by Kozubal et al. and Woods and Kozubal also included a separate evaporative cooler [26,33,94].

Liquid desiccant membrane modules can also be used in vapor compression air conditioners, which enable more efficient latent cooling than a conventional vapor compression machine. This was considered by Bergero and Chiari [98], who showed 50% energy savings over a conventional vapor compression air conditioner for high latent conditions. In this concept, the evaporator cools the liquid desiccant entering the conditioner and the condenser heats the liquid desiccant entering the regenerator. Isetti [99] looked at combining the refrigerant, liquid desiccant, and air into one module in a similar concept that used hollow fibers.

Some private companies are developing technology in this area, but the details are not available in the open literature. ARPA-E funded United Technologies Research Center from 2010 to 2013 [23] to develop a hybrid vapor compression machine using liquid desiccants and membranes. 7AC technologies [100] received private investment to pursue a similar concept.

3.4. Membrane evaporative cooling and humidification

Evaporative cooling and humidification differ only in the goal of the process: evaporative cooling is used to control temperatures,

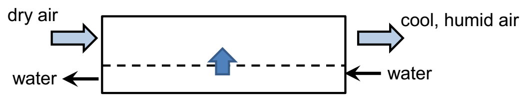

Fig. 14. Membrane humidification or evaporative cooling.

humidification to control humidity. These processes are shown in Fig. 14.

Evaporative cooling has long been known as an energy efficient means of cooling air, but there are still some issues, real or perceived, that limit their use. Membranes have the ability to solve some of these issues.

As discussed by Johnson et al. [28], membranes have a large, fixed surface area for improved heat and mass transfer, especially when using hollow fibers. The small pores of the membrane could also eliminate the passage of microbes and bacteria, providing a sanitary evaporative cooler without the need for frequent cleaning or the use of anti-bacterial agents. Using membranes can also eliminate pumps and sumps by using mains-water pressure to provide low flow rates slightly above the rate of evaporation.

3.4.1. *Module design*

Researchers have focused primarily on hollow-fiber membranes [25,27,28,101], as they offer more surface area and easier construction than flat sheets. Similar to the other membrane devices, flow distribution was an issue in some hollow-fiber prototypes [28]. Much of these distribution problems were found to be worse at high packing fractions [41,43], which are typically preferred based on theoretical performance [34].

Using flat sheets makes it easier to use more than two fluids. While internal cooling or heating is not as helpful as it is for the liquid desiccant dehumidifiers, there are other reasons to have more than two fluids. Conde [92] used flat-sheet membranes to build an indirect evaporative cooler, where the evaporation of water was used to cool a third fluid stream. Kozubal et al. [33] also built an indirect evaporative cooler, but eventually abandoned membranes in favor of flocked or wicked surfaces [26,33].

3.4.2. *System design and analysis*

A key concern for evaporative systems is the treatment of the water prior to entering the membrane module. Using tap water can lead to *fouling*, which is the deposition of solute or particles on the membrane surface [101]. While fouling can be an issue in any evaporative system, fouling of membranes can substantially reduce the evaporation rate by blocking or clogging pores. This fouling can be caused by scaling or biological fouling.

Scaling occurs when the concentrations of certain dissolved salts (primarily calcium carbonate) reach saturation. Charles and Johnson [101] used experiments to indicate how much *wasted water*, which is the amount of water provided above the rate of evaporation, is required to prevent significant scaling. They found that scaling will result in significant flux reduction for wasting flow rates under 30% (70% evaporated, 30% drained). However, their study was not conclusive on how membrane cleaning, where periodic high flow rates of water are used to flood the membrane channels, will prevent scaling. It also did not consider water pretreatment.

Charles and Johnson [101] also looked at biological growth. They found that bacteria do not necessarily need liquid water for growth, but can grow on the airside surface of the membrane, which is warm and humid. This contradicts one of the supposed advantages of membranes; additional research is needed to answer this question more definitively.

Note that scaling is not an issue for liquid desiccant systems, since there is no municipal water. Biological growth is also not an issue because liquid desiccants ensure a low RH environment.

Charles and Johnson [101] also investigated fouling on the airside. They found minimal effect from particle fouling, but they think this could be because their particles were too small. This is an important topic for all of the membrane devices discussed in this review, and deserves further research.

3.5. *Other membrane contactors for HVAC applications*

There are other HVAC applications of membranes that do not fit into the categories above. This is not meant to detract from their potential success. Rather, it simply indicates that they have been studied less than the concepts discussed above.

The first concept is an ERV, like in Section 3.2, but instead of contacting the two airstreams, it pumps a liquid desiccant between two liquid–air membrane contactors [102–105]. The liquid desiccant exchanges heat and moisture with the outgoing exhaust air in one module and with the incoming ventilation air in the other. This enables latent and sensible energy recovery even when the exhaust and supply ventilation ducting are not co-located. While these are ERVs, the modules are similar to the liquid–air modules discussed in Section 3.3. This same research group has also investigated a system using these same liquid–air modules with a desiccant heater and a desiccant chiller so that these modules could be used as a stand-alone air conditioning system [106].

Researchers have also considered membranes for components in absorption heat pumps [107–114], which have long been looked at for their energy-savings potential by using solar or waste thermal energy. The membranes can reduce the size of the heat and mass exchange components (generator, absorber condenser, evaporator) by providing thin liquid films and high surface area. A project was funded by ARPA-E from 2009 to 2012 to develop these membrane components [23].

Researchers have considered other membrane processes for liquid desiccant regeneration: vacuum membrane distillation [115]; electrodialysis [116,117]; and reverse osmosis [118,119]. The latter two operate at lower temperatures than the thermally driven regeneration discussed in Section 3.3. They also are generally driven by electricity, which is available in most buildings, but is generally more expensive than direct combustion, and has more embodied energy [120].

4. Modeling approaches

The behavior of these processes and their performance can be predicted with numerical models. A review of appropriate modeling techniques and their equations is outside of the scope of this review. Instead, this section gives a general overview and cites relevant references.

The most common modeling approach is to discretize the governing equations in the flow direction using a one dimensional finite-difference technique [25,26,47,104]. Some researchers have also looked at NTU-effectiveness approaches [48,51,72,121] where NTU is the calculated number of transfer units for either heat or mass transfer.

In either approach, the key (and more difficult) task is understanding the heat and mass transfer *between* the fluid streams (normal to the flow direction). This is typically calculated with resistance networks. Fig. 15 shows hypothetical vapor pressure and temperature profiles, at steady state, through each *layer* between the fluids for four of the processes discussed above. Each of these layers resists heat and mass transfer.

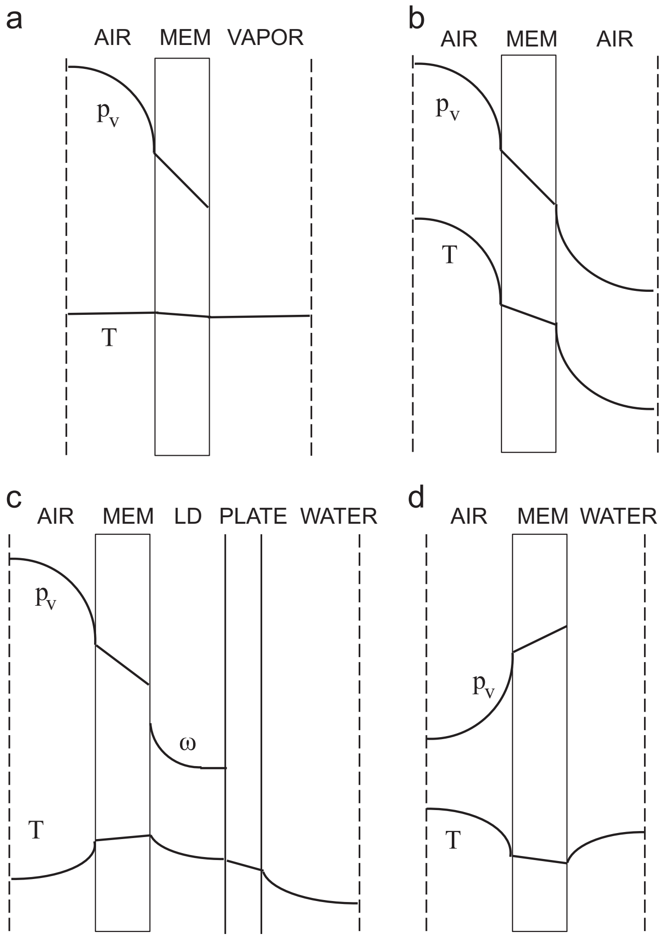

Fig. 15. Steady state temperature (T), vapor pressure (p_v), and liquid desiccant mass fraction (ω) across the membrane and fluid boundary layers for: (a) vacuum membrane dehumidifier; (b) ERV; (c) internally cooled liquid desiccant conditioner; and (d) evaporative cooler. MEM = membrane, LD = liquid desiccant.

The heat flux (q) and molar flux (J) across each of these resistances, i, is modeled with

$$q_i = \Delta T_i / R_{HT,i} \tag{4}$$

$$J_{v,i} = \Delta p_{v,i} / R_{MT,i} \tag{5}$$

where R_{HT} and R_{MT} are respectively the heat and mass transfer resistances, T is the temperature, and p_v is the vapor pressure. We must estimate these resistances for the membrane and for the phases on each side of the membrane. These are discussed briefly in the following sections.

4.1. Transport through the membrane

4.1.1. Mass transport

For describing mass transport through the membrane, we must distinguish between transport through dense membranes and transport through porous membranes. For dense membranes, the transport across the membrane is calculated with

$$J_v = P\frac{\Delta p_{v-mem}}{t} \tag{6}$$

where P is the permeability, t is the membrane thickness, and $\Delta p_{v\text{-}mem}$ is the vapor pressure difference across the membrane. The permeability is defined by a solution–diffusion mechanism [6,8]

$$P = SD \tag{7}$$

where S is the solubility of water vapor in the membrane material, and D is the water vapor diffusivity. Both of these properties depend on the moisture content of the membrane. However, the solubility (i.e., sorption curve slope) seems to be a stronger function of moisture content (see Section 3.2.2).

This model requires an estimate for the permeability. This can be measured directly using standard techniques from ASTM [122]. Alternatively, this can be calculated from the solubility and diffusivity. Solubility can be measured by weighing a sample at different values of RH, as in [77]. The diffusivity can be measured with a transient permeation experiment, the so-called time-lag method [123].

For porous membranes, mass transport is commonly modeled with the dusty gas model [124,125]. The adaptation relevant to transport through membranes for HVAC processes is the same as that used for membrane distillation, and details on this equation and its derivation can be found elsewhere [32]. For the processes discussed in this review, there are two relevant transport mechanisms: Knudsen diffusion, which dominates in smaller pores, and molecular diffusion, which dominates in larger pores. While thermal and surface diffusion are not zero [126], they are small and typically neglected [32]. Viscous flow is also negligible since the absolute pressure gradient is small [32]. High pressure on the liquid side, as long as it is below the breakthrough pressure, will not affect transport. With these assumptions, the molar flux across the membrane is

$$J_v = \frac{1}{RT}\left[\frac{1}{D_M} + \frac{y_{air}}{D_K}\right]^{-1}\frac{\Delta p_{v-mem}}{t} \tag{8}$$

where R is the gas constant and y_{air} is the mole fraction of air. The transport coefficients for Knudsen flow (D_K) and molecular diffusion (D_M) are

$$D_K = \frac{\varepsilon}{\tau}\frac{d_p}{3}\sqrt{\frac{8RT}{\pi M_w}} \tag{9}$$

$$D_M = \frac{\varepsilon}{\tau}D_{wa} \tag{10}$$

where ε is the porosity (open volume/total volume), d_p is the mean pore size, D_{wa} is the molecular diffusion coefficient for water vapor in air, and M_w is the molar mass of water. The deviation of the pores from being straight, cylindrical, and non-interconnected is typically assumed to be captured in the tortuosity factor (τ).

Often the mean pore size, thickness, and porosity can be obtained from the membrane manufacturer, but they can also be estimated using experimental techniques [127,128]. The tortuosity factor can be estimated as a function of the porosity depending on how the membrane is formed [129]. A value of two is assumed by many researchers [130], but this can be low for low porosity membranes. Instead of a single pore size, there is actually a distribution of pore sizes to consider in modeling [131]. However, for diffusion-based processes, using the mean pore size is adequate unless the pore sizes are small enough for Knudsen diffusion to dominate [132].

4.1.2. Heat transport

The key property for heat transport is the thermal conductivity. For dense membranes, this depends on the water content, and is a material property that needs to be measured or obtained from a material property database. As discussed in Section 3, the membrane is a small part of the overall heat transfer resistance; thus, this value is not critical.

The importance of membrane conductivity for processes using porous membranes was also found to be small [86]. In porous membranes, the conductivity of the membrane results from a combination of the conductivity of the air in the pores and the

solid membrane. The parallel and series models bound the problem. The parallel model assumes two independent conduction paths through the air and the solid membrane; the series model assumes conduction through the solid membrane material and then through the air. Experiments have shown actual values to be somewhere between these two extremes [133], and that intermediate models are typically more appropriate.

4.2. Transport through the gas phase

Correlations for the non-dimensional heat and mass transfer coefficients (Nusselt and Sherwood numbers) are usually used to estimate transport through the gas phase. Correlations for heat exchangers are often used, meaning they neglect the effect of the mass flux at the wall. The thermal and moisture diffusivities are approximately equal for air, so these heat transfer correlations can be used for mass transfer as well.

There are some differences, though, between the correlations for heat exchangers and for these membrane devices. Zhang [134] showed that neither constant temperature nor constant heat flux correlations are appropriate for these devices; instead, some combination of the two is best. The geometries of the airflow conduits can also make direct application of these heat-exchanger correlations inappropriate [135]. Below is a discussion about transport in parallel plate channels, in hollow-fiber lumens, and around hollow fibers.

For empty channels in flat-sheet modules, the flow is typically fully developed and laminar. However, the channels are not typically empty; they usually have some type of membrane support. Zhang studied several simple geometries that can be analyzed theoretically [74,136,137]. Sometimes the spacers are more complex, and they obstruct and mix the flow. In these cases, it is difficult to estimate the heat and mass transfer coefficients. Instead, they should be measured, as was done in [64].

For hollow fibers, gas flow through the lumens is fully developed and laminar. But gas flow through the lumens is uncommon due to high pressure losses. An exception is for the membrane vacuum dehumidifier, where the low-pressure vapor is likely to be removed through the lumens. The shell side of a hollow-fiber module is more difficult to model, due primarily to non-uniform spacing of fibers. Some researchers have reviewed this modeling problem and summarized correlations from several studies [41,43].

4.3. Transport through the liquid phase

The liquid phase in HVAC processes is either water or liquid desiccant. For pure water, the transport resistance is small [27,138]. There is no resistance to mass transfer, and since the Prandtl number for water is an order of magnitude larger than that for air, the heat transfer resistance is usually smaller than that of air.

Heat transfer for the liquid desiccant is also relatively fast, and this resistance is small [86]. The small diffusion coefficients mean that mass transfer through the liquid desiccant is slower than heat transfer, although researchers have still shown this to be small compared to the air boundary layer [25,86]. If the flow rate is high enough, a developing-flow correlation is needed [114]. Once the transport coefficient is known, the flux can be calculated with the stagnant film model [139].

5. Research needs and outlook

The development of HVAC membrane processes comes hundreds of years after the invention of the vapor compression air conditioner. These processes continue to evolve as researchers and product developers work to make them competitive with conventional technology. The focus of the research is starting to transition from feasibility and proof of concept to cost and longevity. This is leading to design for manufacturing, accelerated life testing, and demonstrated performance in field installations. However, each technology is at a different stage, and each has its own set of research needs.

Vacuum membrane dehumidification is just past the proof of concept phase. While similar modules have been used for industrial drying applications, the largest module tested for this concept was around 10 cm^2 [40]. Tests on larger modules are needed, including hollow-fiber modules. Research is also needed to better understand how to size these devices, both the membrane module and the compressor. Other configurations can also improve efficiency, primarily ones that lower the compression ratio of the compressor.

Membrane ERVs are commercial products, but there are still some unanswered questions. For example, what is the performance of these units in the field, and how does this compare to the performance measured in the laboratory? Specifically, the measured performance is needed on commercial products for a range of inlet temperatures and humidities. In-the-field monitoring can also show how performance varies with inlet condition, and also how it deteriorates with time. The latter can indicate the useful life of the equipment.

Membrane liquid desiccant dehumidifiers require manufacturing methods that ensure leak-free modules, which can be checked with accelerated life testing of the conditioner and regenerator. While there are still improvements needed in design and manufacturing, field tests of these devices can help determine their reliability.

Membrane prototypes for evaporative cooling and humidification have shown the feasibility of this process. Questions about fouling persist. It is also unclear whether membranes, with their added cost, will be preferred to wicked surfaces.

In addition to these specific research needs, some research would benefit all of these devices. The membrane can still be improved, whether this means higher permeability, higher strength, or reduced cost. But as this review discussed, the air boundary layer resistance is as important, if not more important, than the membrane resistance. Therefore, mass transfer enhancements in the flow channels are needed.

Research on the distribution of airflow is also important, which is incomplete for flat-sheet modules. While the geometry is similar to heat exchangers, unsupported membranes can lead to flow maldistribution that would not be seen in an equivalent heat exchanger with metal plates.

Another potential issue is membrane durability. The success of industrial membrane processes shows that it is possible to operate membrane systems either without fouling or with controlled fouling and scheduled maintenance. The HVAC processes discussed here should have less fouling issues than common membrane filtration processes, where pressure forcibly pushes water through the membrane. However, more research is needed to understand these potential fouling phenomena, and how environmental conditions and pollutants will affect the life of the membrane. This could be degradation of the material from exposure to temperature and humidity cycles, airside particulate fouling on the membrane surface, or degradation from chemical reactions or oxidation of the membrane material.

The outlook for these membrane devices is uncertain. Advances in membrane technology over the previous few decades have enabled these unique devices for HVAC applications, which could potentially lead to more energy efficient products. But more research and development is needed if these products are to compete against the inexpensive and established air conditioning technologies.

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